EÖTVÖS

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United Nations Educational, Scientific and Cultural Organization

Egyesült Nemzetek Nevelésügyi, Tudományos és Kulturális Szervezete

100th anniversary of Roland Eötvös (1848-1919), physicist, geophysicist, and innovator of higher education

Commemorated in association with UNESCO

Eötvös Loránd (1848-1919) fizikus, geofizikus és a felsőoktatás megújítójának 100. évfordulója

Az UNESCO-val közösen emlékezve

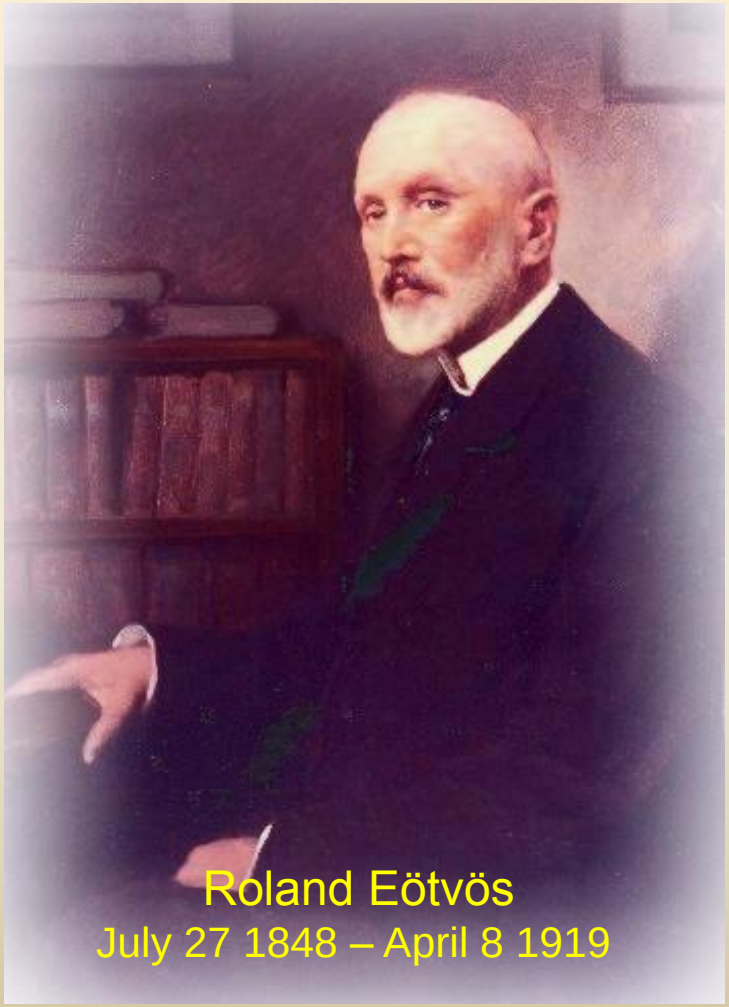
Lajos Völgyesi

# Experiences and results from re-running the Eötvös experiment


World Science Forum

Budapest, November 20. 2019.

The purpose of ***Eötvös experiment*** is to verify the **equivalence principle,** the identity of gravitational and inertial mass, which is the foundation of Einstein's theory of general relativity.

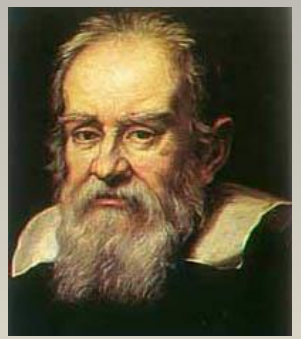

Roland Eötvös
July 27 1848 – April 8 1919

***Weak Equivalence Principle:***
all the laws of motion for freely falling particles are the same as in an unaccelerated reference frame.
(***Gravitational and inertial masses are equal***.)

***Strong Equivalence Principle:***
all the laws of nature are the same in a uniform static gravitational field and the equivalent accelerated reference frame.
(***There is no observable distinction between the local effects of gravity and acceleration***.)

# *The first legendary experiment to prove the*

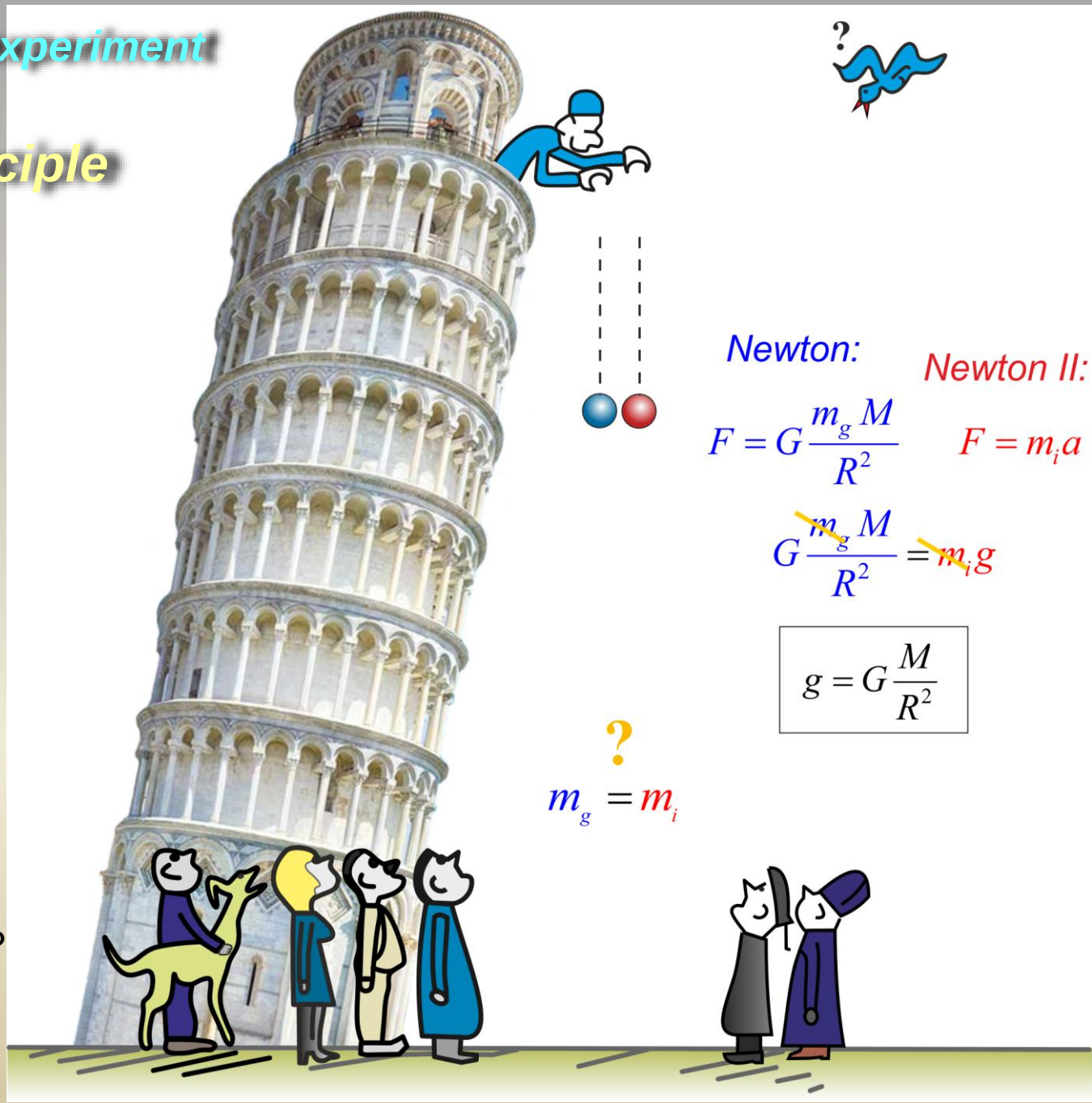
# *Equivalence principle*



Galilo Galilei
1564-1642

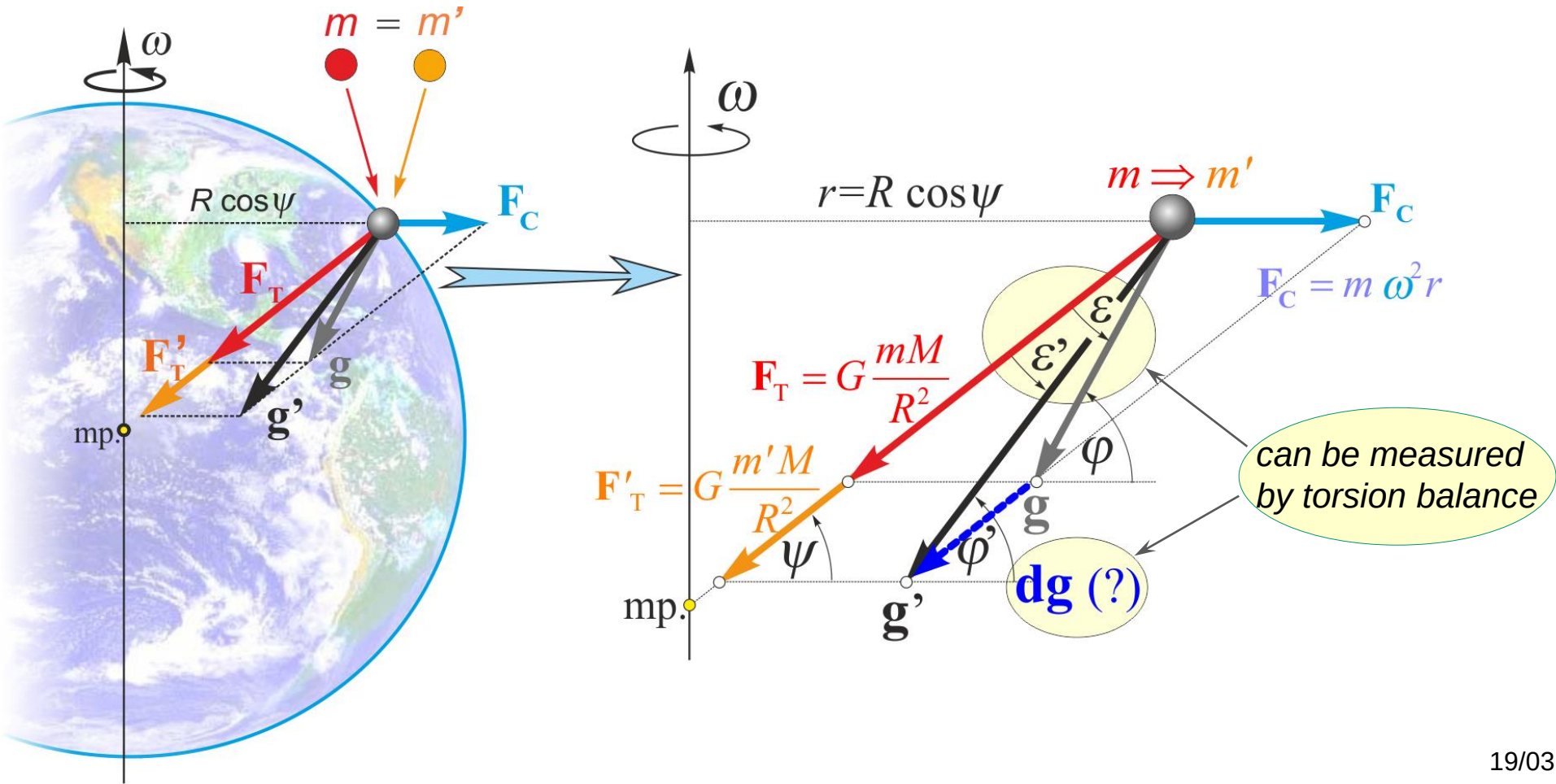
Galilei (?)
Simon Stevin, 1586

*Base question*:
Is the gravitation depends on the material?

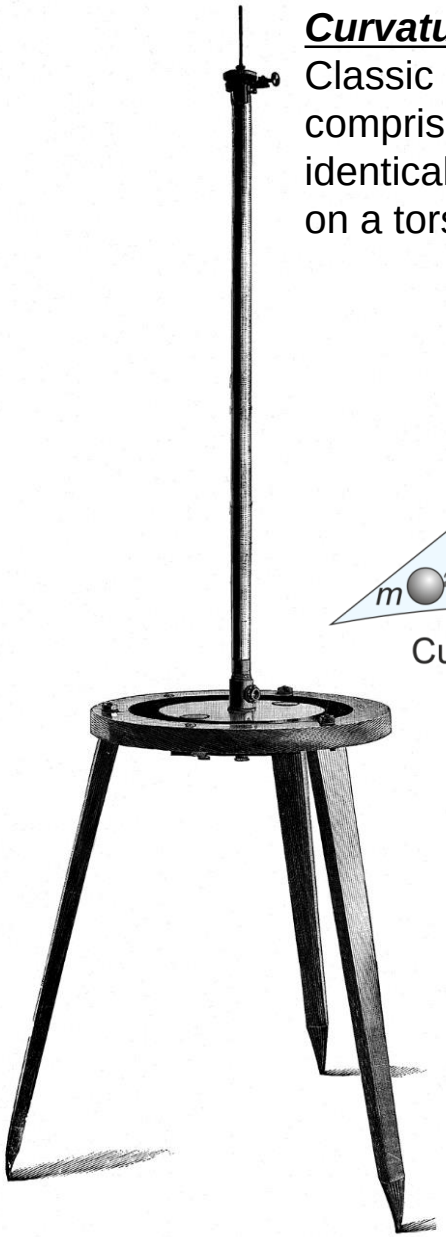


*More than 200 years later Eötvös was the first who examined the equivalence principle very precisely.*

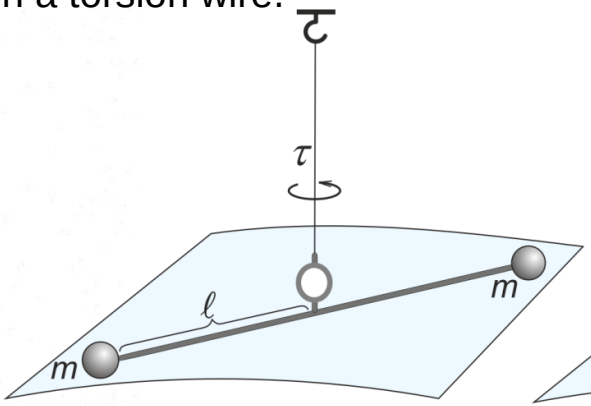
*Base principle of Eötvös experiment*:
Assumption: different materials have different gravitational forces but the same rotational centrifugal force.



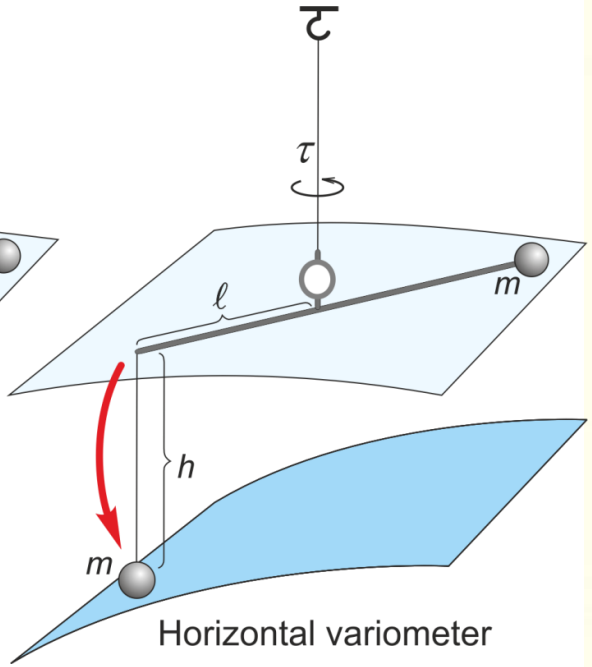
*First Eötvös experiment* in 1896
made by *Curvature Variometer*



***Curvature variometer*** (Eötvös 1890). Classic Coulomb (Cavendish) balance, comprising a horizontal beam with two identical masses at each end, suspended on a torsion wire.

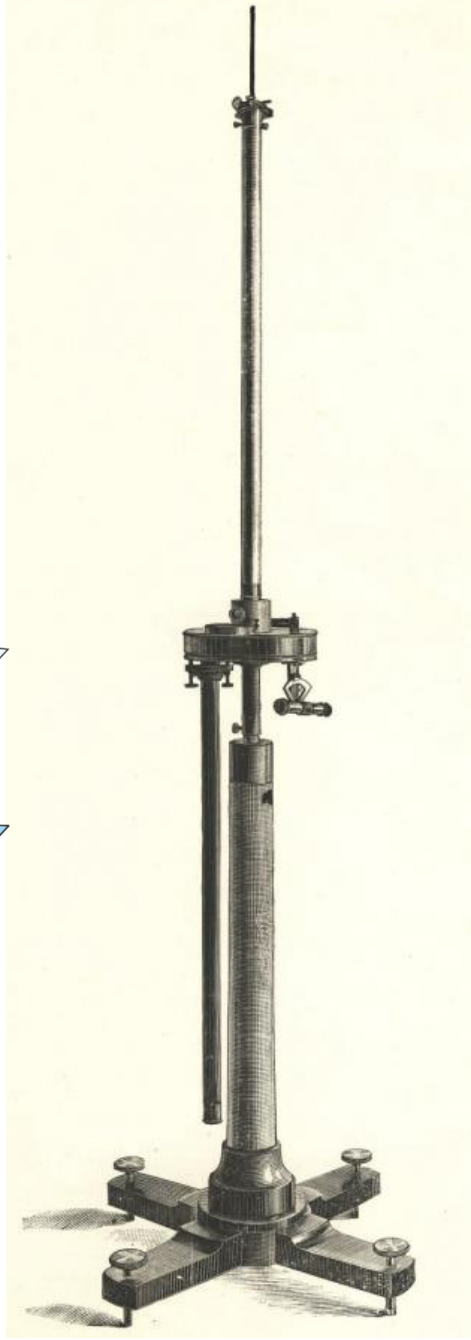


Curvature variometer

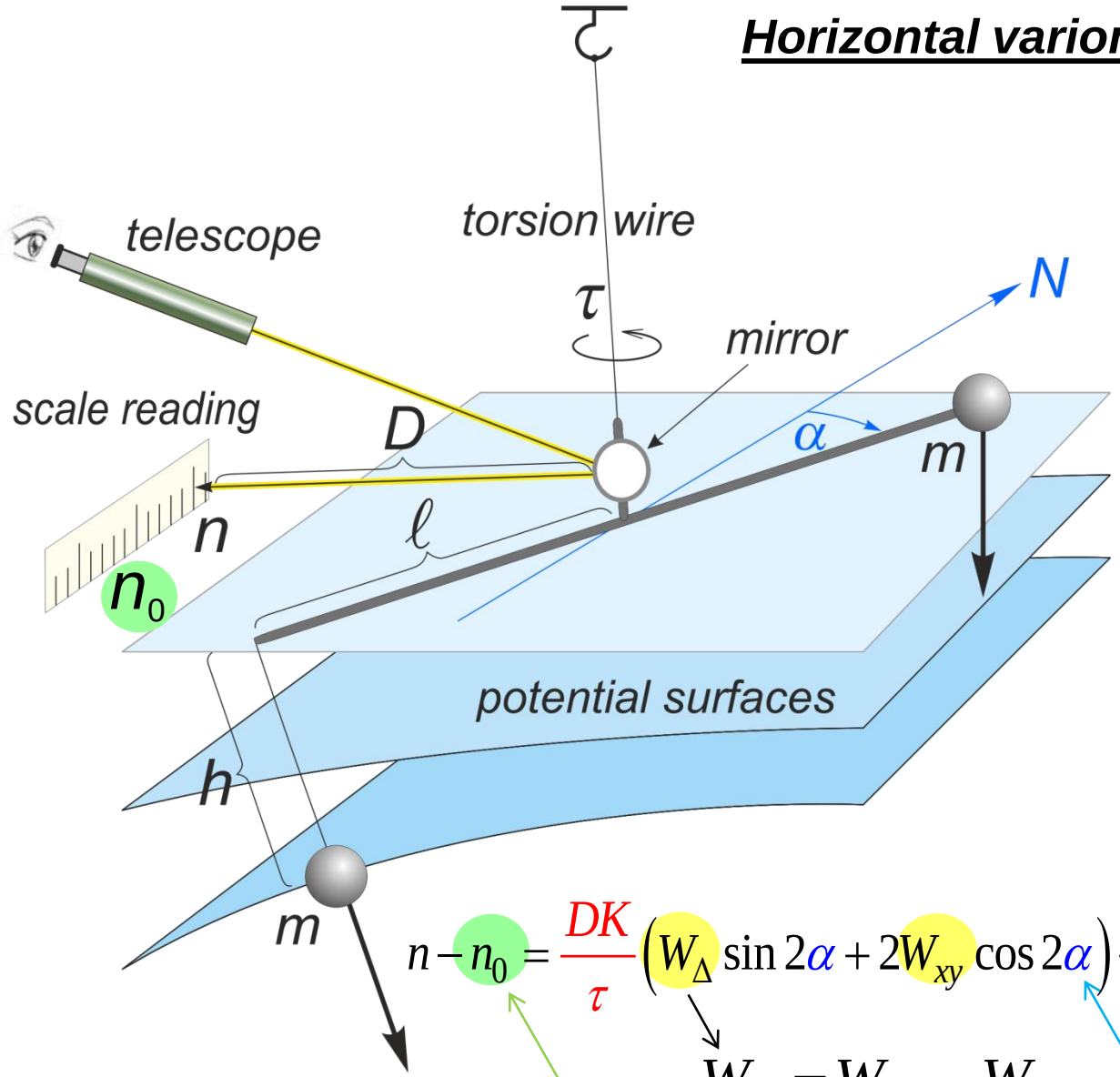


Horizontal variometer

***Horizontal vaiometer*** (Eötvös 1890). The Great invention of Eötvös was that he took one of the masses from the beam and suspended it with a thin wire in a deeper position.



# Horizontal variometer



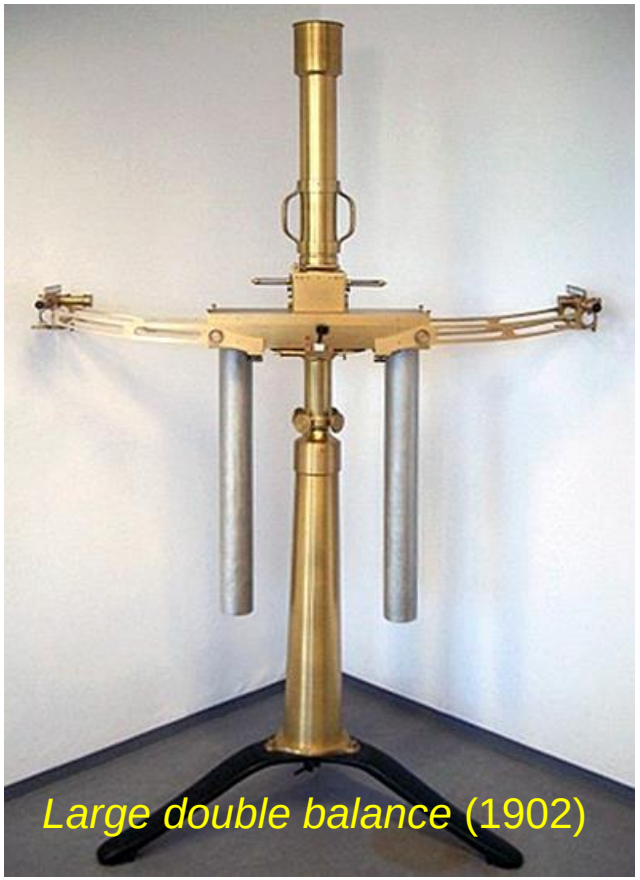

$$\mathbf{E} = \begin{bmatrix} W_{xx} & W_{xy} & W_{xz} \\ W_{yx} & W_{yy} & W_{yz} \\ W_{zx} & W_{zy} & \cancel{W_{zz}} \end{bmatrix}$$

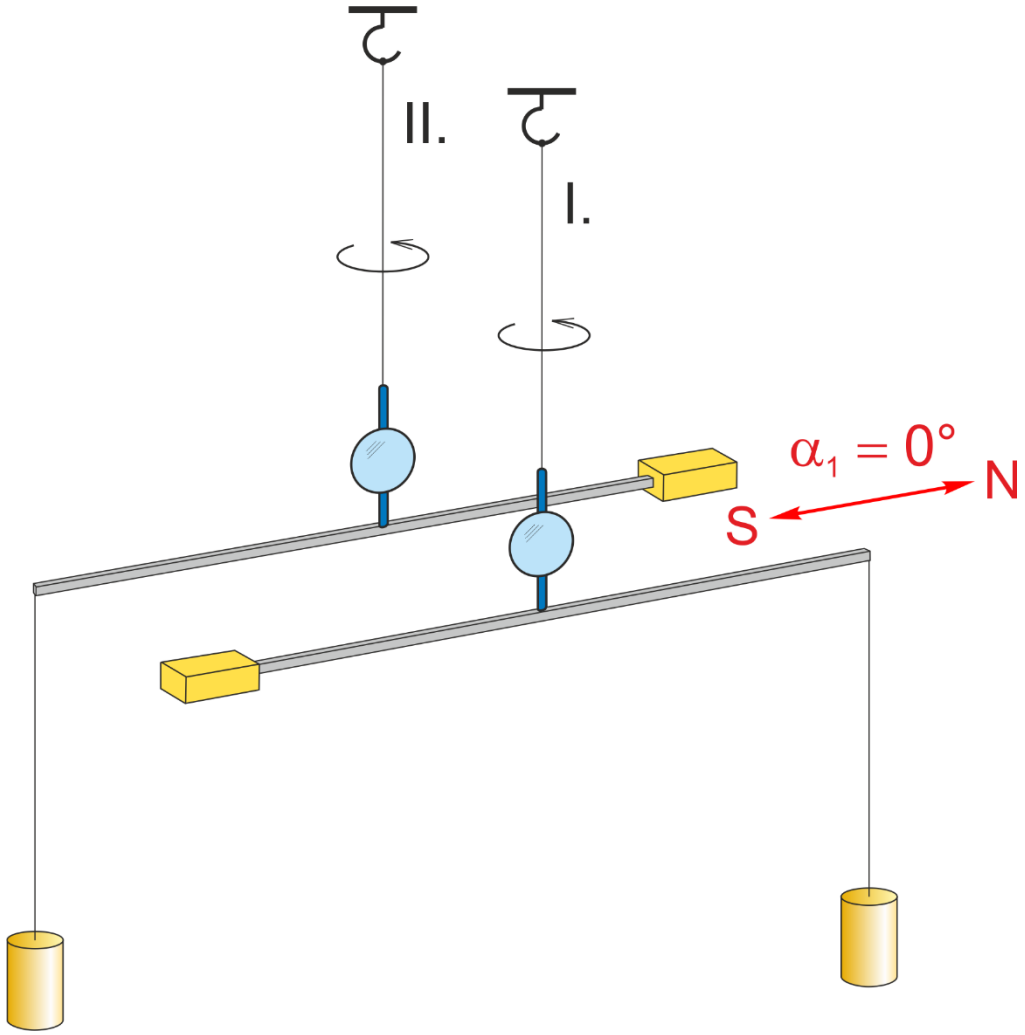
$$n - n_0 = \frac{DK}{\tau}\left(W_\Delta \sin 2\alpha + 2W_{xy}\cos 2\alpha\right) + \frac{2Dhlm}{\tau}\left(W_{zy}\cos\alpha - W_{zx}\sin\alpha\right)$$

$$W_\Delta = W_{yy} - W_{xx}$$

torsion-free position

azimuth



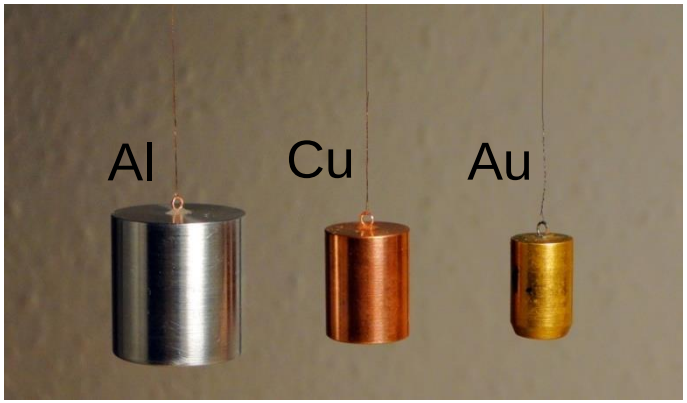



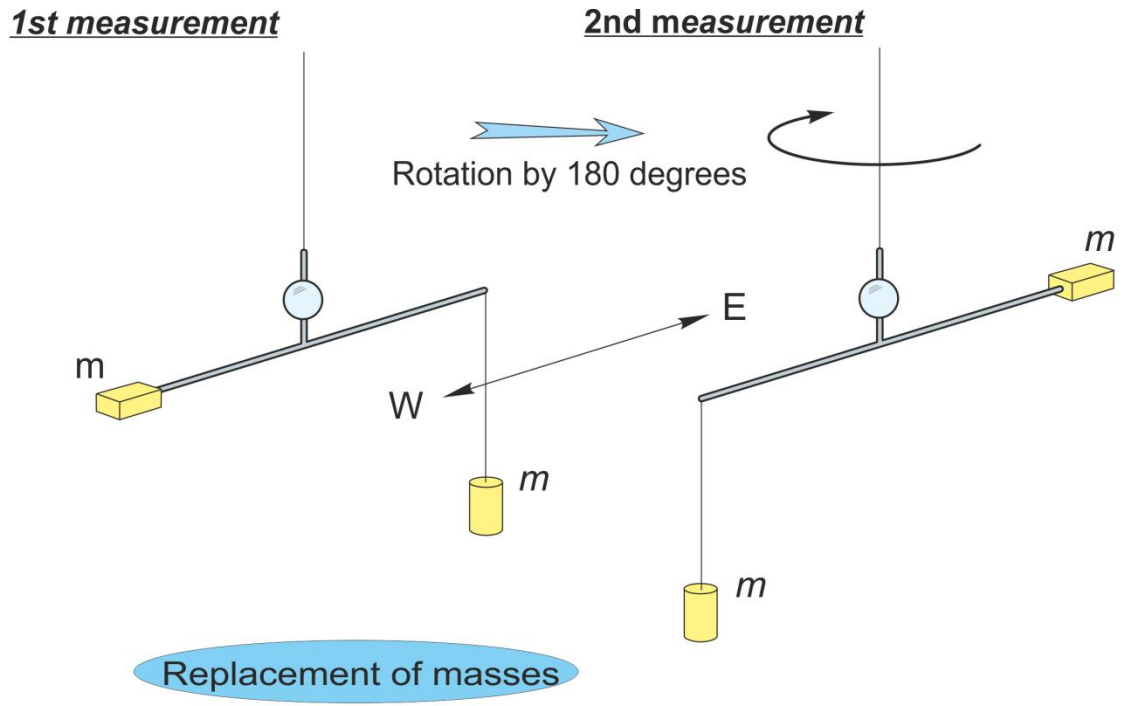

$$n_1 - n_0 = \frac{DK}{\tau}\left(W_\Delta \sin 2\alpha + 2W_{xy}\cos 2\alpha\right) + \frac{2Dhlm}{\tau}\left(W_{zy}\cos\alpha - W_{zx}\sin\alpha\right)$$

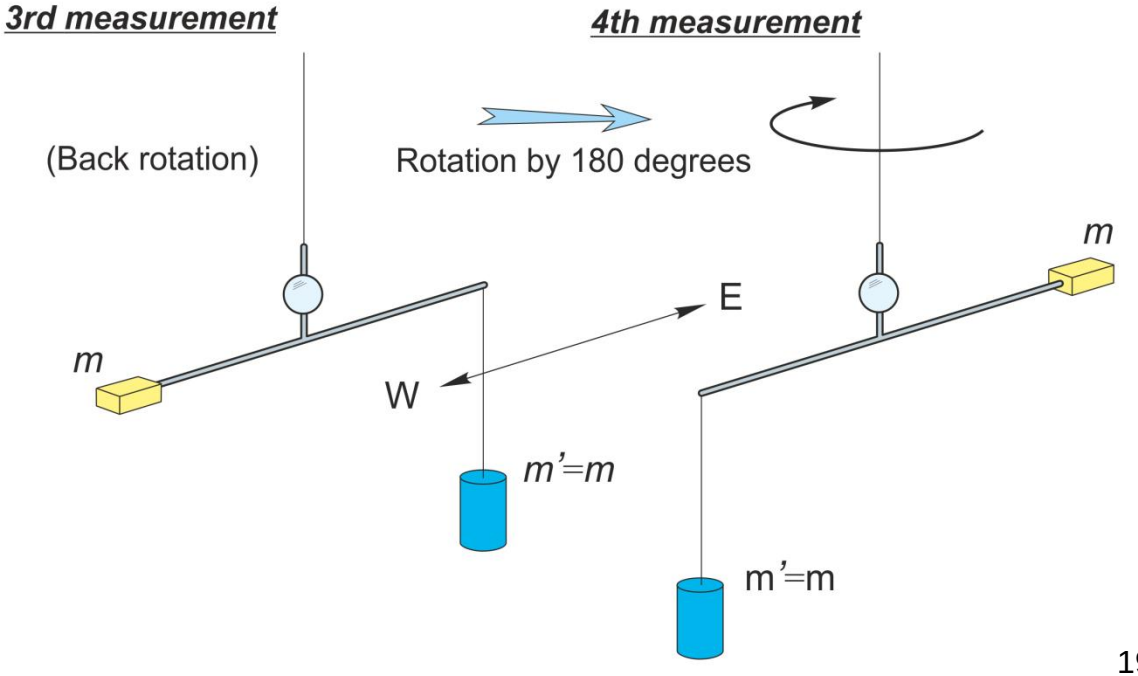
$$n_2 - n_0^* = \frac{DK}{\tau}\left(W_\Delta \sin 2\alpha + 2W_{xy}\cos 2\alpha\right) + \frac{2Dhlm}{\tau}\left(W_{zy}\cos\alpha - W_{zx}\sin\alpha\right)$$

## 4 steps of the Eötvös experiment with Mass exchanging procedure

(In case of a single balance)



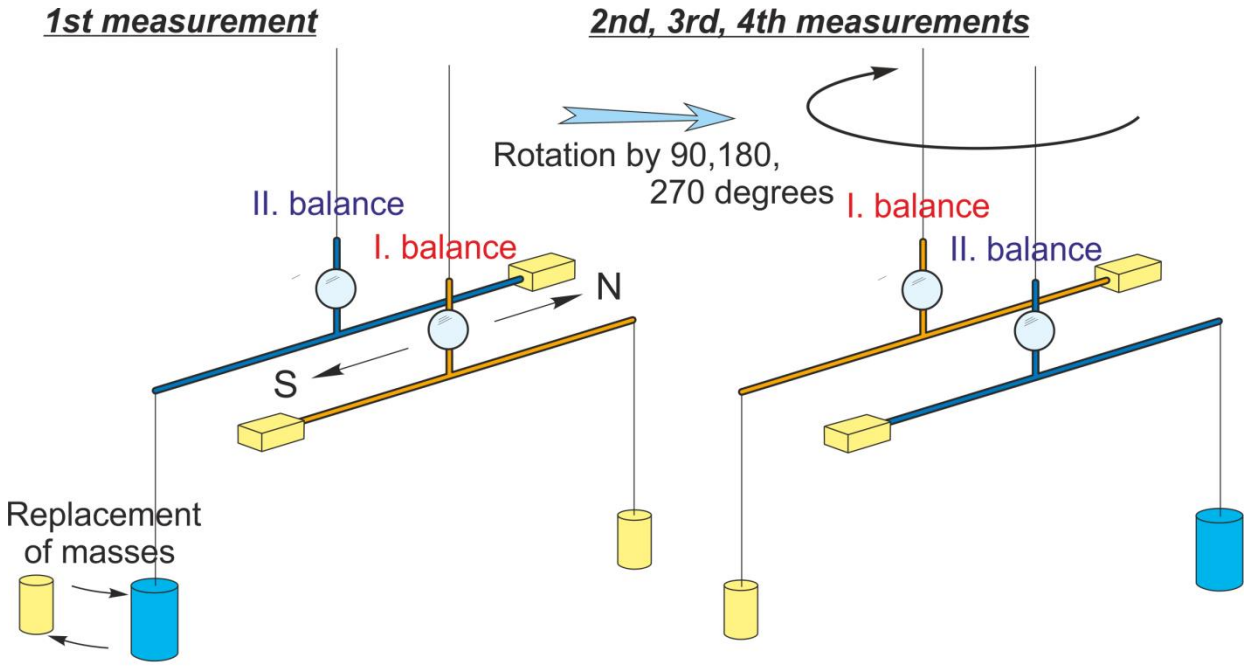



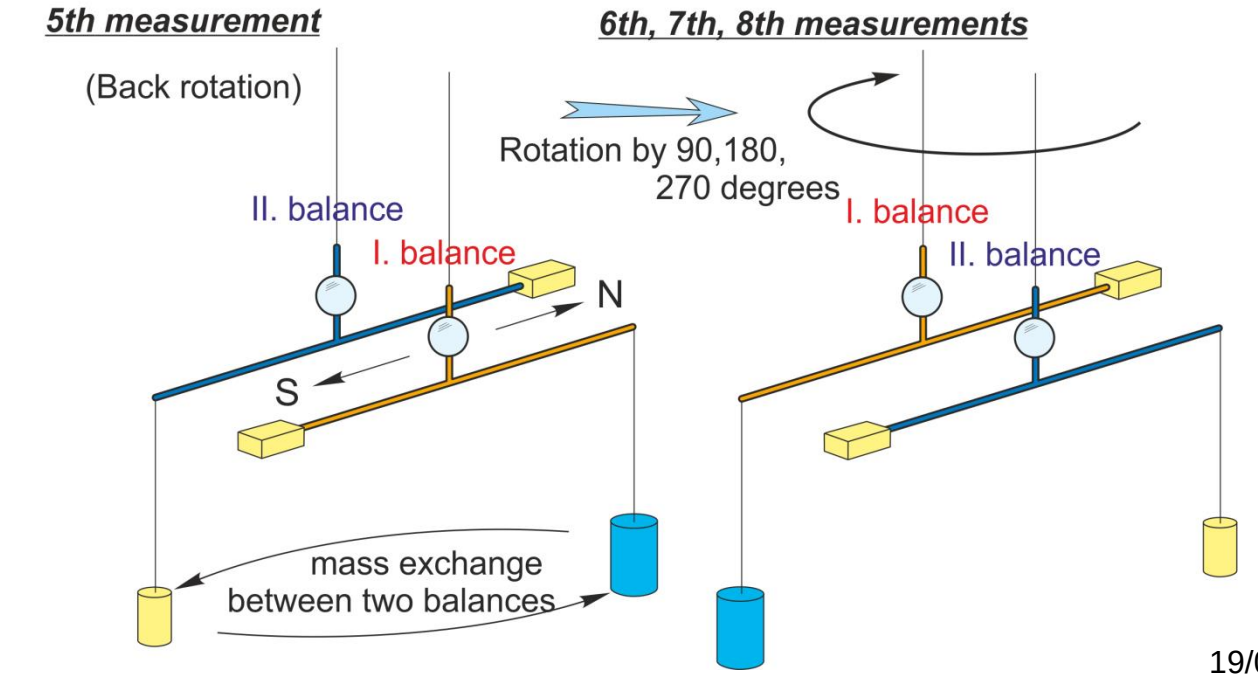



## 8 steps of the Eötvös experiment with Mass exchanging procedure

(In case of a double balance)

***2nd Eötvös-experiment***
***(EPF measurement )*** 1906-1908
***by this*** ***Large Double Balance***



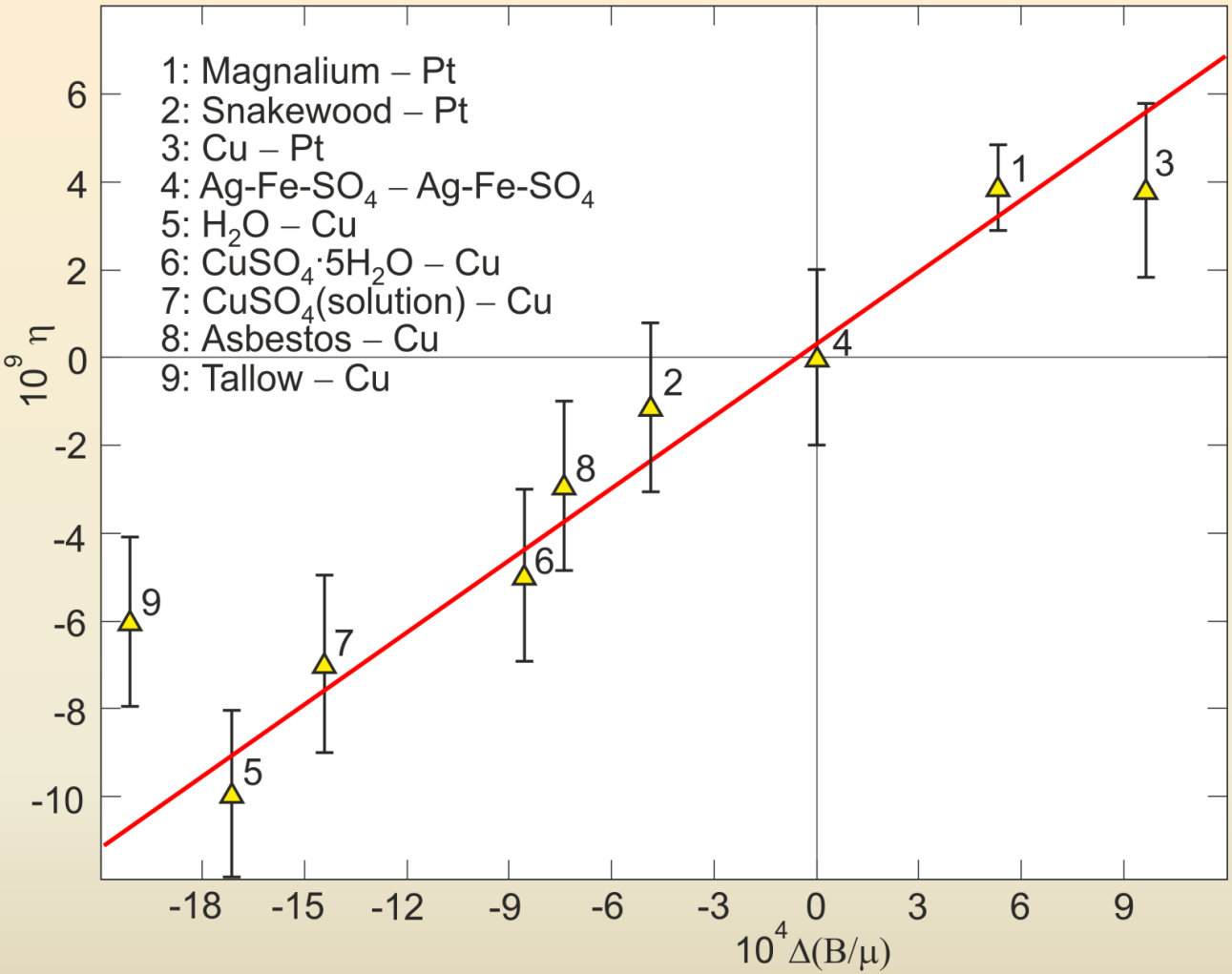
*Specialists know: a very small systematic error can be found in the Eötvös-experiment*

*Fischbach*, 1986:
a possible explanation
of the systematic error

***Fifth force:***
*violation of WEP*

Eötvös (equivalence) parameter:

$$\eta = 2\frac{\left(m_g / m_i\right) - \left(m'_g / m'_i\right)}{\left(m_g / m_i\right) + \left(m'_g / m'_i\right)}$$



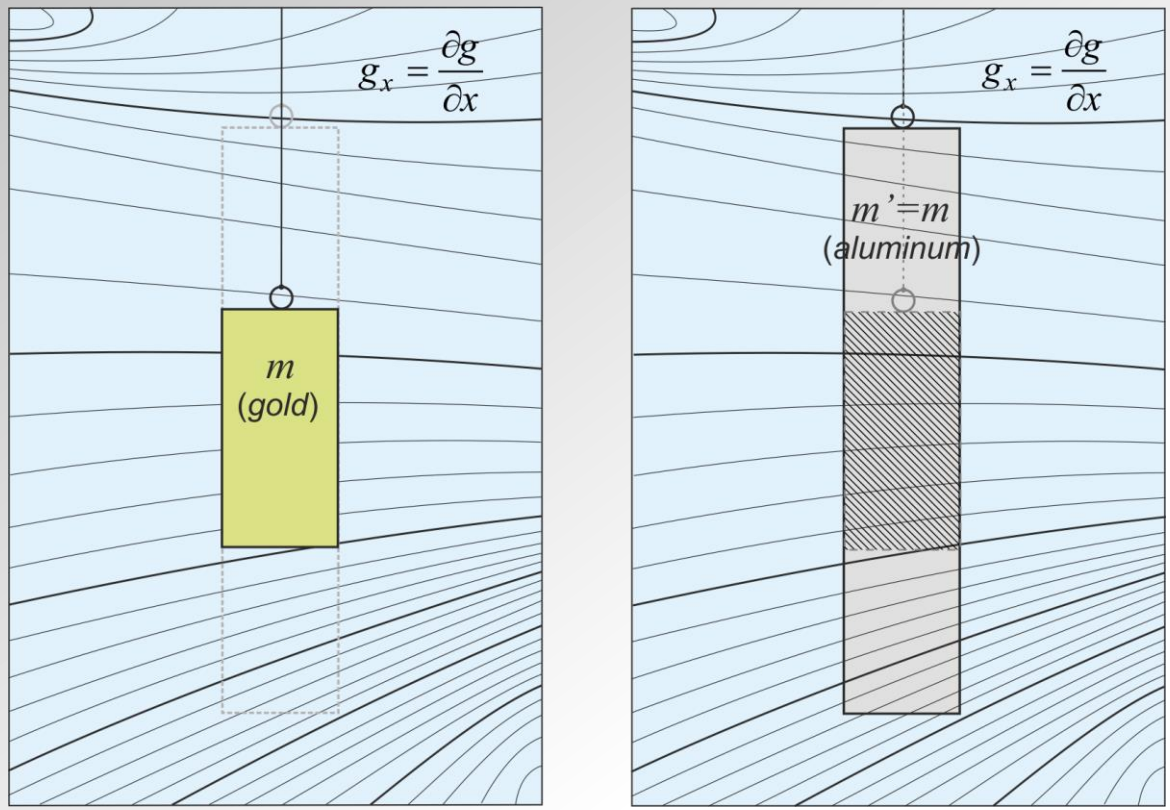

Plot of Eötvös-parameter $\eta$ versus $\Delta(B/\mu)$. $B$ is the baryon number of the substance (the total number of protons and neutrons in the nucleus) and $\mu$ is the mass of the substance in units of the mass of atomic hydrogen. The solid line represents the results of a least squares fit to the data.

*The existence of this 5th force is still the subject of debate.*

In 2017 we decided to celebrate the Eötvös anniversary by re-measuring the Eötvös experiment for validating the equivalence of gravitational and inertial mass.

When we started to study descriptions of the original measurements, we found a possible explanation for the known systematic error:

*Inhomogeneity of gravity gradients around the test masses of the torsion balance cause different gravitational force to different masses having the different size.*




*This recognition makes **necessary the re-running** of the Eötvös-experiment with taking into account the fine structure of gravity gradients around the test masses.*

*AutERBal*

***1st step was to look for the most suitable instrument to re-running the experiment***

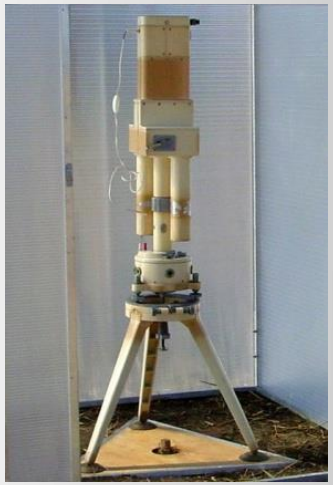
**<u>Eötvös-Pekár</u>** Balance
(*Small Double Balance*)
1930

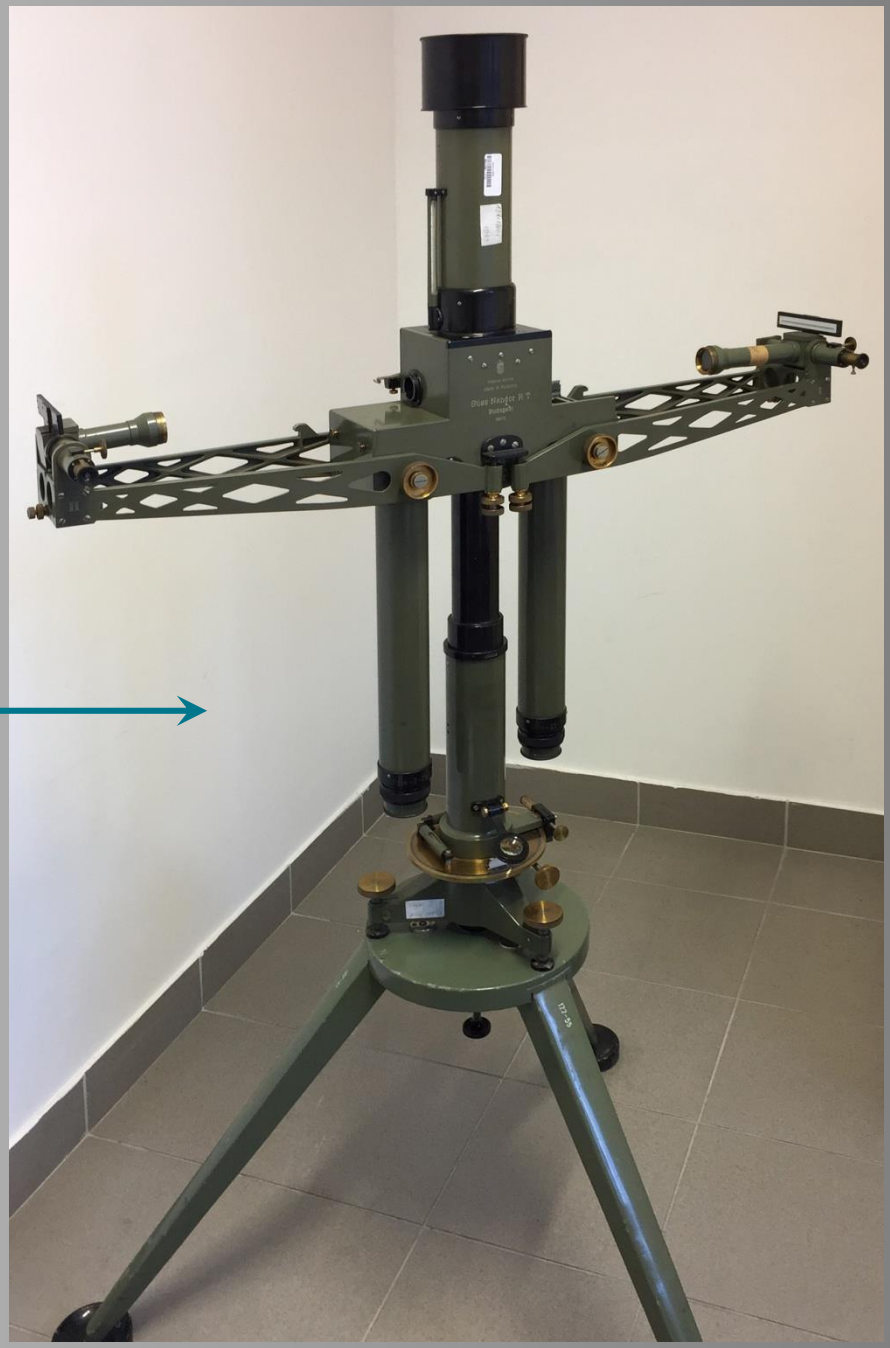
- most accurate and reliable
- easily replaceable masses

(Best usable for equivalence measurements)

*<u>Our developments were focused on this instrument</u>*

*E54*





*The biggest enemy of the torsion balance measurements is the man himself!*

- The mass of the observer's body changes the damped position of the torsion balance,
- Going to instrument the noise of the observer's steps cause ground vibrations, which also disturbs the damped position of the torsion balance.

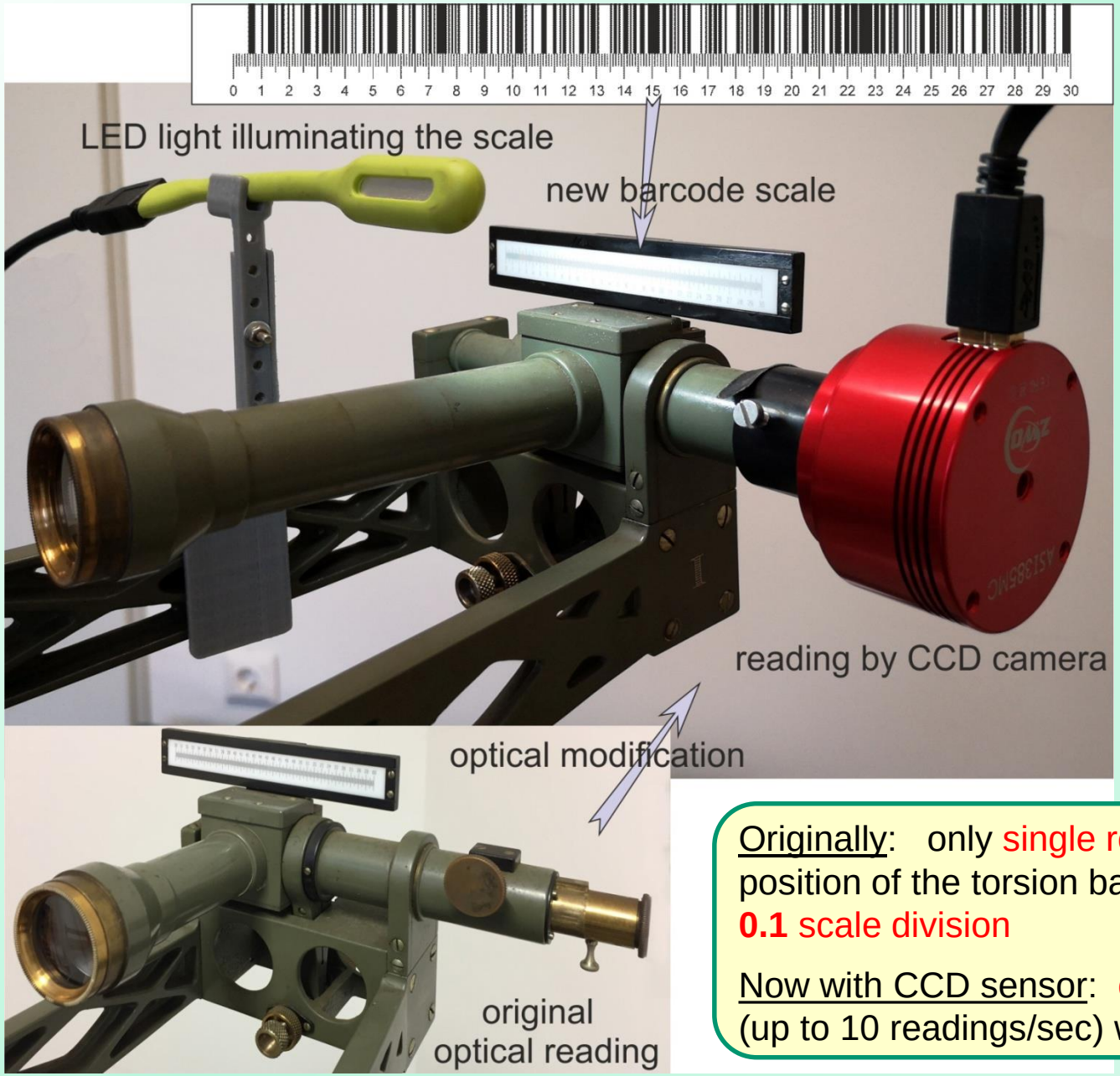
**Solution for these problems** ***two important enhancements:***

1. *Computer-controlled scan on a CCD sensor instead of visual reading*
2. *Using remote-controlled rotation mechanics*

# *Preparing the Eötvös-Pekár torsion balance for the equivlence measurements*

*Preparatory works took place 2 years at the Department of Geodesy and Surveying of BME*

# *Optical modifications of the instrument*




Originally: only single reading after the damped position of the torsion balance with accuracy of **0.1** scale division

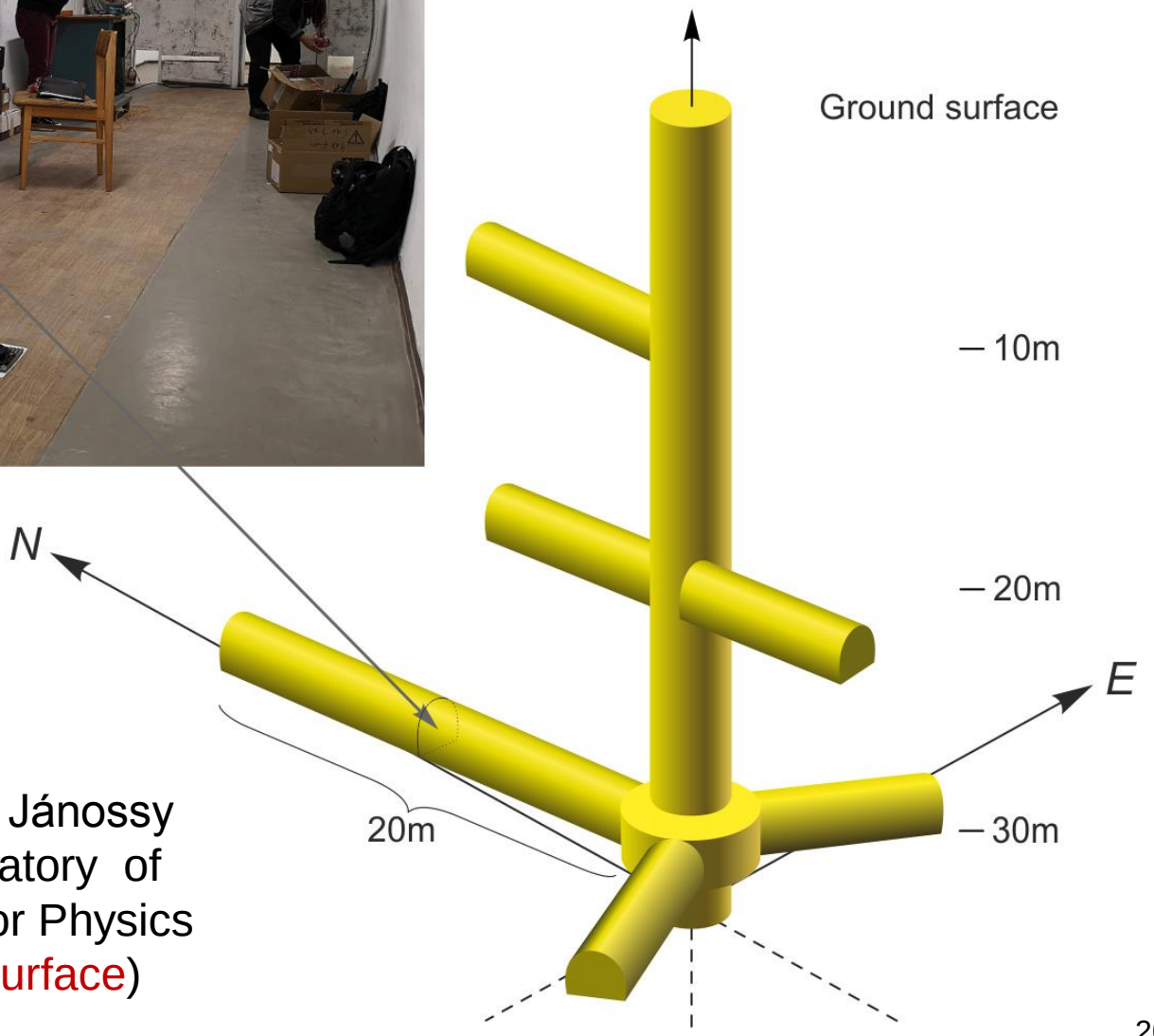
Now with CCD sensor: continuous reading (up to 10 readings/sec) with accuracy of **0.002** div

***The other important modification: Computer-controlled rotation mechanics***

*Using RENISHAW optical encoder, position (azimuth) readout accuracy is under arcseconds*


The mechanism has low weight and low metallic content. We used 3D printing technology to produce most of the parts.

After 2 years preparatory work the instruments were taken to the final measuring site




*Location of measurements*: Jánossy Underground Physics Laboratory of Wigner Researche Center for Physics (in a tunnel 30m under the surface)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Important milestone: after a long preparatory work
our actual equivalence measurements started on May 14. 2019.
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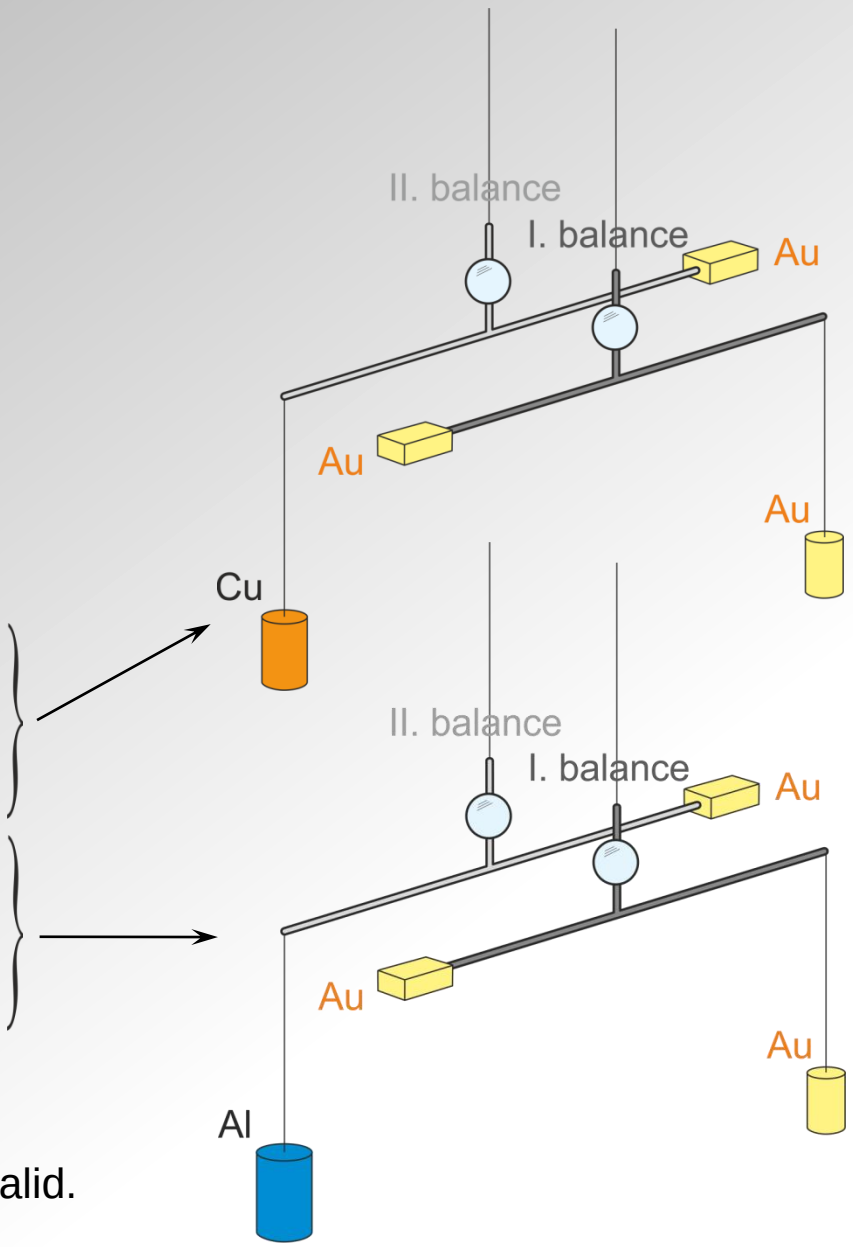
# First (preliminary) results

Eötvös: $10^{-9}$

**Present state: $10^{-10}$**

Eötvös parameter: $$\eta = 2\frac{\left(m_g / m_i\right) - \left(m_g' / m_i'\right)}{\left(m_g / m_i\right) + \left(m_g' / m_i'\right)}$$

| measurement period | material | $\eta$ |
|---|---|---|
| 05.15-05.20. | Au–Au | $0.12 \times 10^{-10}$ |
| 05.15-05.20. | Au–Cu | $0.02 \times 10^{-10}$ |
| 05.21-06.04. | Au–Au | $0.15 \times 10^{-10}$ |
| 05.21-06.04. | Au–Cu | $-0.76 \times 10^{-10}$ |
| 06.17-06.24. | Au–Au | $-0.33 \times 10^{-10}$ |
| 06.17-06.24. | Au–Al | $1.74 \times 10^{-10}$ |
| 06.26-07.03. | Au–Au | $0.09 \times 10^{-10}$ |
| 06.26-07.03. | Au–Al | $0.91 \times 10^{-10}$ |




$\eta$ for the identical masses (Au–Au) should be $0$,
$\eta$ for Au–Cu and Au–Al should be $0$ if WEP is valid.

*The same order of magnitude of errors can be seen during measurements for all pairs of masses!*

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***Present state***: Up to know we did not detect any deviation from the weak equivalence principle with accuracy of $\mathbf{10^{-10}}$ considering the estimated measurement error.

*The equivalence principle, which was first precisely examined in the Eötvös-experiment, is still at the forefront of researches and the torsion balance remains capable for deciding important questions.*

*Accuracy of Eötvös experiment was* $10^{-9}$*, our present state is* $10^{-10}$*, our plan is* $\mathbf{10^{-11}}$*. We should solve a lot of problems, we probably need another 2 or 3 years to continue our experiments to get the final results.*

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# The staff of the experiment:


Völgyesi L.


Szondy Gy.


Tóth Gy.


Ván P.

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Fenyvesi E.


Kiss B.


Péter G.


Harangozó P.


Gróf Gy.


Lévai P.


Barnaföldi G.


Deák L.


Égető Cs.


Somlai L.

(We are *Physicists, geophysicist, geodesists, electrical and mechanical engineers and computer specialists*)